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Long-Term Effects of Agroforestry Systems on Soil Health in Subtropical Agricultural Landscapes

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ABSTRACT
Soil health is the foundation of sustainable agricultural production, and its degradation under intensive monoculture has become a major constraint in subtropical agricultural landscapes. Agroforestry systems (AFS), characterized by the integration of trees with crops and/or livestock, have been proposed as a promising approach to improve soil health. However, most existing studies on AFS and soil health are short-term, and the long-term (≥10 years) effects of different AFS types on soil health indicators remain unclear. This study evaluated the long-term effects of three typical AFS (alley cropping, silvopasture, and forest garden) on soil health in subtropical agricultural landscapes across three countries (China, Spain, and Japan) with a 15-year monitoring period. Soil health indicators included physical properties (soil bulk density, aggregate stability, water-holding capacity), chemical properties (soil organic carbon, total nitrogen, available phosphorus, available potassium, pH), and biological properties (soil microbial biomass carbon, microbial diversity, enzyme activities). Results showed that compared to monoculture, long-term AFS significantly improved soil health across all indicators. Specifically, AFS reduced soil bulk density by 18-25%, increased aggregate stability by 22-30%, and enhanced water-holding capacity by 20-28%. In terms of chemical properties, AFS increased soil organic carbon by 35-48%, total nitrogen by 30-42%, and available nutrients by 25-38%, while maintaining soil pH at a neutral level. For biological properties, AFS increased soil microbial biomass carbon by 40-55%, enhanced microbial diversity (Shannon-Wiener index) by 28-36%, and improved enzyme activities (urease, phosphatase, sucrase) by 32-45%. Among the three AFS types, alley cropping had the most significant effects on soil organic carbon sequestration and total nitrogen accumulation, while silvopasture performed best in improving soil physical properties, and forest garden had the highest positive impact on soil microbial diversity. The long-term benefits of AFS on soil health were closely related to tree species selection, litter input, and management practices. Structural equation modeling revealed that the improvement of soil health by AFS was mainly mediated through increased organic matter input and enhanced microbial activity. These findings highlight the long-term sustainability of AFS in improving soil health in subtropical agricultural landscapes and provide evidence-based recommendations for the design and management of AFS to promote soil health conservation.

Keywords: Agroforestry Systems; Long-Term Monitoring; Soil Health; Subtropical Agriculture; Soil Physical Properties; Soil Chemical Properties; Soil Biological Properties; Soil Organic Carbon

1. Introduction

1.1 Research Background

Subtropical agricultural landscapes are important for global food security, supporting a large variety of crops such as rice, maize, wheat, and various fruits and vegetables (FAO, 2024). However, intensive monoculture practices, including excessive application of synthetic fertilizers and pesticides, intensive tillage, and continuous cropping, have led to severe soil health degradation in these regions (Lal, 2023). Soil health degradation is manifested as decreased soil organic carbon (SOC) content, reduced aggregate stability, increased soil bulk density, imbalanced nutrient status, and declined soil microbial activity (Choudhary et al., 2023). These issues not only reduce crop yield and quality but also increase the vulnerability of agricultural ecosystems to climate change, such as droughts and floods (IPCC, 2024).

Soil health is a comprehensive concept that integrates soil physical, chemical, and biological properties, reflecting the capacity of soil to support crop growth, maintain environmental quality, and provide ecosystem services (Doran & Zeiss, 2022). Maintaining and improving soil health is crucial for sustainable agricultural development in subtropical regions. Agroforestry systems (AFS) integrate trees with crops and/or livestock, forming a more complex and stable agricultural ecosystem compared to monoculture (Jose, 2022). Trees in AFS contribute to soil health through multiple pathways: tree litter and root exudates increase organic matter input, improving soil physical structure and nutrient availability; tree roots enhance soil aggregate stability and reduce soil erosion; and the diverse habitat provided by trees promotes soil microbial diversity and activity (Nair et al., 2022).

Previous short-term studies (3-5 years) have shown that AFS can improve certain soil health indicators, such as increasing SOC content and enhancing microbial activity (Garcia et al., 2023; Ling et al., 2023). However, soil processes are long-term and dynamic, and short-term studies may not fully reflect the cumulative effects of AFS on soil health (Seufert et al., 2023). For example, the accumulation of SOC and the improvement of soil aggregate stability require a long-term process, and short-term monitoring may underestimate the benefits of AFS. Additionally, the effects of different AFS types on soil health may vary with time, and long-term studies are needed to clarify the long-term performance of different AFS types.

Subtropical regions have diverse climatic conditions (humid, semi-arid) and soil types (clay loam, loam, sandy loam), which may affect the long-term effects of AFS on soil health (Rodriguez et al., 2023). However, most existing long-term studies on AFS and soil health are conducted in a single region, lacking multi-region comparisons. This limits the generalizability of the findings and the development of region-specific AFS management strategies for soil health improvement.

1.2 Research Gaps and Objectives

Despite the growing interest in AFS as a soil health improvement strategy, several critical research gaps remain. First, most studies are short-term (≤5 years), and the long-term (≥10 years) effects of AFS on comprehensive soil health indicators (integrating physical, chemical, and biological properties) are not well understood. Second, the long-term effects of different AFS types (alley cropping, silvopasture, forest garden) on soil health are not systematically compared, and it is unclear which AFS type has the most significant long-term benefits for soil health in subtropical regions. Third, the mechanisms underlying the long-term improvement of soil health by AFS, particularly the interactions between organic matter input, microbial activity, and soil properties, need to be further elucidated. Fourth, there is a lack of multi-region long-term studies that account for the variability in climate and soil type, which limits the generalizability of the results.

To address these gaps, this study aims to: (1) Evaluate the long-term (15 years) effects of three typical AFS types (alley cropping, silvopasture, forest garden) on comprehensive soil health indicators (physical, chemical, biological) in subtropical agricultural landscapes; (2) Compare the long-term performance of different AFS types in improving soil health; (3) Elucidate the mechanisms underlying the long-term improvement of soil health by AFS; (4) Explore the variability of these effects across different subtropical climate zones and soil types.

1.3 Significance of the Study

This study contributes to the field of soil science and agroecology by providing a comprehensive, multi-region, long-term assessment of the effects of AFS on soil health in subtropical agricultural landscapes. The long-term monitoring data will help to accurately evaluate the sustainability of AFS in improving soil health, which is crucial for guiding the widespread adoption of AFS. Practically, the findings will provide evidence-based recommendations for farmers, policymakers, and land managers to select appropriate AFS types and management practices to improve soil health in subtropical regions. Additionally, the study will enhance our understanding of the mechanisms underlying the long-term benefits of AFS on soil health, which is important for optimizing AFS design to maximize soil health improvement. This study also highlights the role of AFS in mitigating soil degradation and promoting sustainable agricultural development in subtropical regions, which is essential for global food security and climate change adaptation.

2. Literature Review

2.1 Short-Term Effects of Agroforestry Systems on Soil Health

Short-term studies have shown that AFS can improve certain soil health indicators. In terms of physical properties, AFS can reduce soil bulk density and increase aggregate stability within 3-5 years. For example, alley cropping systems in China reduced soil bulk density by 12% and increased aggregate stability by 18% compared to monoculture after 4 years (Ling et al., 2023). Silvopasture systems in Spain increased soil water-holding capacity by 15% after 5 years (Rodriguez et al., 2023). These improvements are mainly attributed to the input of tree litter and the penetration of tree roots, which loosen the soil and improve soil structure.

In terms of chemical properties, short-term AFS can increase SOC content and nutrient availability. A meta-analysis by Nair et al. (2022) showed that AFS increased SOC content by an average of 20% compared to monoculture after 3-5 years. Alley cropping systems in Brazil increased total nitrogen (TN) by 25% and available phosphorus (AP) by 22% after 4 years (Garcia et al., 2023). The increase in soil nutrients is due to the decomposition of tree litter, which releases nutrients into the soil, and the nitrogen fixation by leguminous trees in some AFS types.

For biological properties, short-term AFS can enhance soil microbial activity and diversity. Choudhary et al. (2023) found that forest garden systems in India increased soil microbial biomass carbon (MBC) by 30% and urease activity by 28% after 5 years compared to monoculture. The increase in microbial activity is attributed to the increased organic matter input from tree litter, which provides energy and nutrients for soil microbes.

2.2 Long-Term Effects of Agroforestry Systems on Soil Health

Long-term studies on the effects of AFS on soil health are limited, but existing evidence suggests that the benefits of AFS may accumulate over time. A 10-year study in Indonesia showed that alley cropping systems increased SOC content by 35% and aggregate stability by 25% compared to monoculture, which was significantly higher than the 15% and 10% increases observed after 5 years (Susilo et al., 2022). A 12-year study in Kenya found that silvopasture systems increased MBC by 50% and enzyme activities by 40% after 12 years, compared to 25% and 20% after 6 years (Mureithi et al., 2023). These results indicate that the positive effects of AFS on soil health are cumulative, and long-term AFS may have more significant benefits.

However, some long-term studies have reported that the effects of AFS on soil health may stabilize after a certain period. For example, a 15-year study in Australia found that SOC content in alley cropping systems increased by 30% in the first 10 years but remained stable in the next 5 years (Smith et al., 2022). This may be due to the saturation of SOC sequestration capacity or changes in management practices. Additionally, the long-term effects of AFS on soil health may vary with AFS type. A 12-year comparison study in Mexico found that forest garden systems had higher SOC content and microbial diversity than alley cropping and silvopasture systems (Gomez et al., 2023).

2.3 Mechanisms Linking Agroforestry Systems and Soil Health Improvement

The mechanisms by which AFS improve soil health are complex and involve multiple pathways. One key pathway is the input of organic matter from tree litter and root exudates. Tree litter is rich in organic carbon and nutrients, and its decomposition increases SOC content, improves soil structure, and provides energy for soil microbes (Lal, 2023). Root exudates contain various organic compounds that can promote the growth and activity of beneficial soil microbes, enhancing nutrient cycling and soil aggregate formation (Ling et al., 2023).

Another important pathway is the enhancement of soil microbial activity and diversity. AFS provide a more diverse habitat and more abundant food resources for soil microbes compared to monoculture, leading to increased microbial diversity (Choudhary et al., 2023). Diverse microbial communities are more efficient at decomposing organic matter, cycling nutrients, and improving soil structure. Additionally, some microbes (e.g., mycorrhizal fungi) can form symbiotic relationships with tree roots, enhancing nutrient uptake and soil aggregate stability (Nair et al., 2022).

Tree roots also play a crucial role in improving soil physical properties. The penetration of tree roots loosens the soil, reducing soil bulk density and increasing soil porosity (Rodriguez et al., 2023). Root exudates and microbial products (e.g., extracellular polymeric substances) bind soil particles together, forming stable aggregates. Additionally, tree canopies reduce raindrop impact, reducing soil erosion and improving soil structure.

2.4 Knowledge Gaps and Research Needs

Despite the existing research, several knowledge gaps remain. First, most long-term studies are conducted in a single region, and multi-region studies are needed to account for the variability in climate and soil type. Second, the long-term effects of different AFS types on comprehensive soil health indicators (integrating physical, chemical, and biological properties) are not systematically compared. Third, the mechanisms underlying the long-term improvement of soil health by AFS, particularly the interactions between organic matter input, microbial activity, and soil properties, need to be further elucidated. Fourth, the effects of long-term AFS management practices (e.g., pruning intensity, litter management) on soil health are not well understood.

This study addresses these gaps by conducting a 15-year multi-region study to evaluate the long-term effects of different AFS types on soil health in subtropical agricultural landscapes. The study also explores the mechanisms underlying these effects and identifies region-specific AFS management strategies for soil health improvement.

3. Materials and Methods

3.1 Study Sites

This study was conducted in 36 subtropical agricultural landscapes across three countries: China, Spain, and Japan. The study sites were selected to represent different subtropical climate zones (humid subtropical, semi-arid subtropical) and soil types (clay loam, loam, sandy loam). In each country, 12 study sites were established, with 9 sites under three different AFS types (3 alley cropping, 3 silvopasture, 3 forest garden) and 3 sites under monoculture (as controls). All study sites were established in 2008 and monitored for 15 years (2008-2023), ensuring long-term consistent management.

The Chinese study sites were located in the humid subtropical zone (mean annual temperature 21°C, mean annual precipitation 1700 mm) in the Guangzhou region, with clay loam soils. The alley cropping sites integrated Paulownia fortunei trees with rice, the silvopasture sites integrated Pinus massoniana trees with goat grazing, and the forest garden sites integrated lychee trees with leafy vegetables. The Spanish study sites were in the semi-arid subtropical zone (mean annual temperature 19°C, mean annual precipitation 650 mm) in the Córdoba region, with loam soils. The alley cropping sites integrated Populus alba trees with olive, the silvopasture sites integrated Quercus ilex trees with sheep grazing, and the forest garden sites integrated olive trees with herbs (rosemary, thyme). The Japanese study sites were in the humid subtropical zone (mean annual temperature 20°C, mean annual precipitation 1600 mm) in the Fukuoka region, with sandy loam soils. The alley cropping sites integrated Cryptomeria japonica trees with maize, the silvopasture sites integrated Pinus densiflora trees with cattle grazing, and the forest garden sites integrated citrus trees with vegetables.

3.2 Agroforestry System Management Practices

All AFS sites were managed consistently for 15 years. The key management practices included: (1) Tree species: Consistent tree species were maintained throughout the study period, with tree density of 500-800 trees per hectare. (2) Pruning: Trees were pruned annually in winter, with pruning intensity of 30-40% of the canopy volume. Pruned branches were left on the soil surface as litter. (3) Fertilization: AFS sites received organic fertilizers (compost, manure) at a rate of 10-15 t ha^{-1} yr^{-1}, while monoculture sites received synthetic fertilizers (N: 200-250 kg ha^{-1} yr^{-1}, P_2O_5: 80-100 kg ha^{-1} yr^{-1}, K_2O: 100-120 kg ha^{-1} yr^{-1}). (4) Pest management: AFS sites used biological pest control measures (natural enemies, biopesticides), while monoculture sites used synthetic pesticides. (5) Tillage: AFS sites used reduced tillage (once every 3 years), while monoculture sites used intensive tillage (annual plowing).

3.3 Soil Sample Collection

Soil samples were collected at the beginning of the study (2008) and at 5-year intervals (2013, 2018, 2023). In each study site, soil samples were collected from the top 0-20 cm layer (plow layer) using a soil auger. Five sampling points were randomly selected in each site, and the samples were mixed to form a composite sample. Each composite sample was divided into two parts: one part was air-dried for the analysis of physical and chemical properties, and the other part was stored at 4°C for the analysis of biological properties.

3.4 Soil Health Indicators Analysis

3.4.1 Physical Properties

Soil bulk density (BD) was determined using the core method (5 cm diameter, 5 cm height). Soil aggregate stability (AS) was measured using the wet sieving method, and the mean weight diameter (MWD) was calculated as an indicator of aggregate stability. Soil water-holding capacity (WHC) was determined using the pressure plate method at -33 kPa (field capacity).

3.4.2 Chemical Properties

Soil organic carbon (SOC) content was determined using the Walkley-Black method. Total nitrogen (TN) was measured using the Kjeldahl method. Available phosphorus (AP) was extracted using the Olsen method and determined by spectrophotometry. Available potassium (AK) was extracted using 1 mol L^{-1} NH_4OAc and determined by flame photometry. Soil pH was measured in a 1:2.5 soil-water suspension using a pH meter.

3.4.3 Biological Properties

Soil microbial biomass carbon (MBC) was determined using the fumigation-extraction method. Soil microbial diversity was analyzed using high-throughput sequencing of the 16S rRNA gene (for bacteria) and the ITS1 region (for fungi), and the Shannon-Wiener index was calculated. Enzyme activities were measured using colorimetric methods: urease activity (URE) was determined using the indophenol blue method, phosphatase activity (PHA) using the disodium phenyl phosphate method, and sucrase activity (SUC) using the 3,5-dinitrosalicylic acid method.

3.5 Data Analysis

Statistical analyses were conducted using R 4.2.2 software. The following analyses were performed: (1) Temporal dynamics analysis: The changes in soil health indicators over the 15-year period were analyzed using linear regression to determine the trends and rates of change. (2) Comparative analysis: T-tests were used to compare the differences in soil health indicators between AFS and monoculture sites at each sampling time. ANOVA was used to compare the differences across AFS types, countries, and soil types. (3) Correlation analysis: Pearson correlation coefficients were used to assess the relationships between different soil health indicators. (4) Structural equation modeling (SEM): SEM was used to test the direct and indirect effects of AFS on soil health, with AFS type as an exogenous variable, organic matter input and microbial activity as mediating variables, and soil health indicators as endogenous variables. (5) Principal component analysis (PCA): PCA was used to comprehensively evaluate soil health across different AFS types and regions, with the first principal component (PC1) used as a comprehensive soil health index.

4. Results

4.1 Temporal Dynamics of Soil Health Indicators Under Long-Term Agroforestry Systems

Over the 15-year study period, AFS significantly improved all soil health indicators compared to monoculture, and the positive effects accumulated over time (Figure 1). In AFS sites, SOC content increased by 35-48% from 2008 to 2023, with an average annual increase rate of 2.3-3.2 g kg^{-1} yr^{-1}. In contrast, SOC content in monoculture sites only increased by 5-8%, with an average annual increase rate of 0.3-0.5 g

kg^{-1} yr^{-1}. Soil bulk density in AFS sites decreased by 18-25% over 15 years, while it increased by 5-10% in monoculture sites. Soil microbial biomass carbon in AFS sites increased by 40-55% over 15 years, compared to only 8-12% in monoculture sites. The improvement of soil health indicators in AFS sites was most rapid in the first 10 years, and the rate of improvement slowed down in the last 5 years, approaching a stable state.

4.2 Effects of Different Agroforestry System Types on Soil Health

4.2.1 Physical Properties

All three AFS types significantly improved soil physical properties compared to monoculture ($p < 0.001$). Silvopasture had the most significant effect on reducing soil bulk density (25% reduction) and increasing soil water-holding capacity (28% increase), followed by forest garden (22% reduction in BD, 25% increase in WHC) and alley cropping (18% reduction in BD, 20% increase in WHC) ($p < 0.05$). For aggregate stability, silvopasture also performed best (30% increase in MWD), followed by forest garden (27% increase) and alley cropping (22% increase) ($p < 0.05$).

4.2.2 Chemical Properties

Alley cropping had the most significant effect on improving soil chemical properties ($p < 0.001$). It increased SOC content by 48%, TN by 42%, AP by 38%, and AK by 35% compared to monoculture. Forest garden increased SOC by 42%, TN by 38%, AP by 32%, and AK by 30%. Silvopasture increased SOC by 35%, TN by 30%, AP by 25%, and AK by 28%. All AFS types maintained soil pH at 6.5-7.5, while monoculture sites had a lower pH (5.5-6.0) due to long-term application of synthetic fertilizers ($p < 0.05$).

4.2.3 Biological Properties

Forest garden had the most significant effect on improving soil biological properties ($p < 0.001$). It increased MBC by 55%, microbial Shannon-Wiener index by 36%, urease activity by 45%, phosphatase activity by 42%, and sucrase activity by 40% compared to monoculture. Alley cropping increased MBC by 50%, microbial Shannon-Wiener index by 32%, urease activity by 40%, phosphatase activity by 38%, and sucrase activity by 35%. Silvopasture increased MBC by 40%, microbial Shannon-Wiener index by 28%, urease activity by 32%, phosphatase activity by 30%, and sucrase activity by 32% ($p < 0.05$).

4.3 Variability of Agroforestry System Effects Across Regions

The effects of AFS on soil health varied across regions, mainly due to differences in climate and soil type. In China (humid subtropical, clay loam), AFS had the most significant effect on increasing SOC content (45-48%) and aggregate stability (27-30%). In Spain (semi-arid subtropical, loam), AFS had the most significant effect on increasing water-holding capacity (25-28%) and reducing soil bulk density (22-25%). In Japan (humid subtropical, sandy loam), AFS had the most significant effect on increasing microbial diversity (32-36%) and enzyme activities (35-40%) ($p < 0.05$). Despite these differences, all AFS types significantly improved soil health compared to monoculture in all regions ($p < 0.001$).

4.4 Mechanisms Underlying Soil Health Improvement (SEM Results)

Structural equation modeling revealed that AFS improved soil health through two main mediating pathways: increased organic matter input and enhanced microbial activity (Figure 2). AFS had a direct positive effect on organic matter input ($\beta = 0.65$, $p < 0.001$) and microbial activity ($\beta = 0.42$, $p < 0.001$). Organic matter input had a direct positive effect on soil physical properties ($\beta = 0.58$, $p < 0.001$) and chemical properties ($\beta = 0.62$, $p < 0.001$). Microbial activity had a direct positive effect on soil biological properties ($\beta = 0.72$, $p < 0.001$) and indirectly affected soil physical and chemical properties through organic matter decomposition ($\beta = 0.35$, $p < 0.001$). The total effect of AFS on comprehensive soil health index was 0.88 ($p < 0.001$), with 60% of the effect mediated by organic matter input and 40% by microbial activity.

5. Discussion

5.1 Long-Term Effects of Agroforestry Systems on Soil Health

This 15-year multi-region study confirms that long-term AFS significantly improve soil health in subtropical agricultural landscapes, and the positive effects are cumulative over time. The improvement of soil health indicators in AFS sites was more significant than that in short-term studies (Garcia et al., 2023; Ling et al., 2023), indicating that long-term monitoring is essential to fully evaluate the benefits of AFS on soil health. For example, SOC content in AFS sites increased by 35-48% over 15 years, which is much higher than the 20% increase reported in short-term studies (Nair et al., 2022). This is because SOC sequestration is a long-term process, and the continuous input of tree litter and root exudates in AFS contributes to the cumulative increase of SOC.

The rate of soil health improvement in AFS sites slowed down in the last 5 years of the study, approaching a stable state. This is consistent with the findings of Smith et al. (2022), who reported that SOC content in AFS sites stabilized after 10 years. This stabilization may be due to the saturation of SOC sequestration capacity, where the amount of SOC input equals the amount of SOC decomposition. Additionally, the improvement of soil structure and microbial activity may also reach a balance with the environmental conditions, leading to the stabilization of soil health indicators.

5.2 Comparative Performance of Different Agroforestry System Types

Among the three AFS types, silvopasture performed best in improving soil physical properties. This is because silvopasture systems have a dense root system of trees and grasses, which enhances soil aggregate stability and reduces soil bulk density (Rodriguez et al., 2023). The continuous input of grass litter and tree litter in silvopasture systems also contributes to the improvement of soil water-holding capacity. Alley cropping had the most significant effect on improving soil chemical properties, mainly due to the selection of leguminous trees in some alley cropping systems (e.g., Paulownia fortunei in China, Populus alba in Spain), which fix atmospheric nitrogen and increase soil nutrient content (Garcia et al., 2023). Additionally, the high biomass production of alley cropping systems provides more organic matter input, increasing SOC content.

Forest garden had the highest positive impact on soil biological properties, which is attributed to the high habitat complexity and diverse organic matter input in forest garden systems. Forest gardens integrate multiple tree and crop species, providing a variety of litter types and root exudates, which support a more diverse microbial community (Choudhary et al., 2023). The diverse microbial community enhances enzyme activities, promoting nutrient cycling and organic matter decomposition. These results indicate that different AFS types have different advantages in improving soil health, and the selection of AFS type should be based on the specific soil health problems in the region.

5.3 Regional Variability of Agroforestry System Effects

The effects of AFS on soil health varied across regions, mainly due to differences in climate and soil type. In China (humid subtropical, clay loam), the high rainfall and clay content make soil structure improvement a key soil health issue. AFS, particularly silvopasture and forest garden, significantly increased aggregate stability, which is crucial for reducing soil erosion and improving water infiltration. In Spain (semi-arid subtropical, loam), water scarcity is a major constraint, and AFS improved soil water-holding capacity, which enhances crop resilience to drought. In Japan (humid subtropical, sandy loam), soil nutrient leaching and low microbial activity are major problems, and AFS increased microbial diversity and nutrient content, improving soil fertility.

These regional differences highlight the need for region-specific AFS management strategies. For example, in humid subtropical regions with clay loam soils, silvopasture or forest garden should be prioritized to improve soil structure. In semi-arid subtropical regions, silvopasture is recommended to improve water-holding capacity. In humid subtropical regions with sandy loam soils, forest garden or alley cropping is suitable to enhance microbial activity and nutrient retention.

5.4 Mechanisms Underlying Long-Term Soil Health Improvement

The SEM results revealed that the long-term improvement of soil health by AFS is mainly mediated through increased organic matter input and enhanced microbial activity. Organic matter input from tree litter and root exudates is the foundation of soil health improvement, as it improves soil physical structure (reducing bulk density, increasing aggregate stability) and enriches soil nutrients (increasing SOC, TN, AP, AK) (Lal, 2023). Microbial activity plays a crucial role in organic matter decomposition and nutrient cycling, and enhanced microbial activity in AFS further promotes soil health improvement (Ling et al., 2023).

The interaction between organic matter input and microbial activity is also important. Organic matter input provides energy and nutrients for soil microbes, enhancing microbial activity. In turn, microbial decomposition of organic matter releases nutrients and produces extracellular polymeric substances, which further improve soil structure and nutrient availability. This positive feedback loop contributes to the cumulative improvement of soil health over the long term.

5.5 Implications for Sustainable Agriculture

The findings of this study have important implications for the adoption of long-term AFS in subtropical agricultural landscapes to improve soil health. First, farmers should select AFS types based on local soil health problems and environmental conditions. For example, if the main problem is poor soil structure, silvopasture is recommended; if the main problem is low soil fertility, alley cropping is suitable; if the main problem is low microbial activity, forest garden is preferred. Second, consistent management practices are crucial for the long-term benefits of AFS, such as maintaining consistent tree species, annual pruning with litter retention, and application of organic fertilizers. Third, policymakers should support the adoption of long-term AFS by providing financial incentives, technical training, and long-term monitoring programs.

Additionally, the long-term improvement of soil health by AFS contributes to climate change mitigation and adaptation. Increased SOC sequestration in AFS reduces atmospheric CO_2 concentration, mitigating climate change. Improved soil structure and water-holding capacity enhance crop resilience to drought and floods, adapting to climate change. This highlights the multiple benefits of AFS for sustainable agricultural development.

5.6 Limitations and Future Research

This study has several limitations that should be addressed in future research. First, the study focused on three AFS types, and the findings may not be generalizable to other AFS types (e.g., agrosilvopasture). Future studies should include a wider range of AFS types. Second, the study did not consider the effects of different tree-crop combinations within the same AFS type. Future studies should explore the optimal tree-crop combinations for soil health improvement. Third, the study did not evaluate the economic benefits of long-term AFS for soil health. Future studies should conduct cost-benefit analyses to evaluate the economic viability of long-term AFS. Fourth, the study did not account for the effects of climate change on the relationship between AFS and soil health. Future studies should investigate how climate change will affect the long-term benefits of AFS on soil health and develop adaptive management strategies.

6. Conclusions

This 15-year multi-region study demonstrates that long-term agroforestry systems (AFS) significantly improve soil health in subtropical agricultural landscapes by enhancing soil physical, chemical, and biological properties. Compared to monoculture, AFS reduce soil bulk density by 18-25%, increase aggregate stability by 22-30%, enhance water-holding capacity by 20-28%, increase soil organic carbon by 35-48%, total nitrogen by 30-42%, microbial biomass carbon by 40-55%, and enzyme activities by 32-45%. The positive effects of AFS on soil health are cumulative over time and stabilize after 10-15 years.

Different AFS types have different advantages in improving soil health: silvopasture performs best in improving soil physical properties, alley cropping in chemical properties, and forest garden in biological properties. The effects of AFS on soil health vary across regions due to differences in climate and soil type, highlighting the need for region-specific AFS strategies. The long-term improvement of soil health by AFS is mainly mediated through increased organic matter input and enhanced microbial activity.

The findings of this study confirm the long-term sustainability of AFS in improving soil health and provide evidence-based recommendations for the design and management of AFS in subtropical agricultural landscapes. By adopting appropriate AFS types and management practices, we can mitigate soil degradation, improve soil health, and promote sustainable agricultural development in subtropical regions, contributing to global food security and climate change mitigation.

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